DESIGN OF WEARABLE TENSEGRITY STRUCTURES FOCUSING ON THE TENSION PROPAGATION FUNCTION THROUGHOUT THE BODY

Wakashima, Hiroki;
Kishino, Kodai;
Iizuka, Shinpei;
Tamachi, Masahiro;
Wesugi, Shigeru

Waseda University

ABSTRACT

Humans are able to perform skilful movements by coordinating muscles throughout the body. It has been revealed that not only neural mechanisms but also direct and dynamic interactions between body parts contribute to muscular coordination. Tensegrity, accurately biotensegrity, can be considered to the basic mechanism for the interactions. Tensegrity structures are composed of tensile and compressive components, and are lighter and more flexible than existing rigid structures. The authors investigated designing wearable tensegrity structures for extending human motor ability, especially assisting in carrying heavy objects. Based on Flemons' spine model, we devised a columnar tensegrity structure that can be expanded to the size of the whole body, and connected each of four columns to the front and back of the body on right and left side. The wearable tensegrity structures can deform flexibly due to tension distribution when external force is applied, and follow the human motions in twisting trunk and walking. Experimental results in carrying heavy objects showed that some muscle activities around hip and knee tended to decrease by using the structures when those joints extended.

Keywords: Tensegrity, Motion assist, Design for interfaces, Bio-inspired design / biomimetics, Case study

Contact:
Kishino, Kodai
Waseda University
Japan
kodai_kishino@ruri.waseda.jp

Cite this article: Wakashima, H., Kishino, K., Iizuka, S., Tamachi, M., Wesugi, S. (2023) 'Design of Wearable Tensegrity Structures Focusing on the Tension Propagation Function throughout the Body', in *Proceedings of the International Conference on Engineering Design (ICED23),* Bordeaux, France, 24-28 July 2023. DOI:10.1017/pds.2023.129

1 INTRODUCTION

Humans can perform skilful movements by coordinating muscles throughout the body. It is known that neural mechanisms are involved in the coordination of multiple muscles. Even if the same neural signals are sent to skeletal muscles to perform a specific action, the muscles may behave differently due to changes in the external environment. In other words, it is difficult to establish a one-to-one correspondence between neural signals and movements. Recently, it has been revealed that not only neural mechanisms but also direct and dynamic interactions between body parts contribute to skilful movements. In terms of the body structure, tension in elastic organs such as muscles, tendons, and fascia transfers force between multiple parts of the body, and the motion is organized as a mechanical interaction. This pathway of tension transmission in the body is called an "anatomy trains," and has attracted attention in the field of exercise therapy, where it is actually used in therapeutic practice (Myers, 2014). Tension in the muscles that move a certain joint is transmitted not only to that joint, but also to distant parts of the body. This tension propagates throughout the body, thereby controlling body movements through the interaction between muscles. For example, in the throwing motion, the interaction of tension contributes to the coordination of multiple muscles when force is transmitted to the shoulder, elbow, and wrist, and to the maintenance of body stiffness for balance during the throw.

Focusing on such tension transmission function throughout the body, we study a way to extend the motor function without electrical assistance. This includes producing a large force output by linking forces, or distributing external forces applied to a part of the body to the entire body by connecting each part of the body to the entire body.

In this study, we design wearable structures based on the tension transmission mechanism for assisting physical movement, especially in carrying heavy load. In general, movement assist suits are classified into two types: endoskeleton and exoskeleton (Inose et al., 2017). An endoskeleton type does not have an external frame, and a load is supported by the skeletal structures inside the body. This type assists movement with elastic materials typically, therefore, it is lightweight, allowing less restricted movements. The device in this type is designed for lifting relatively lightweight objects (2-10 kg). On the other hand, an exoskeleton type is composed of a highly rigid external frame with joints and actuators to assist movements. In contrast to the endoskeleton type, a load is supported by a frame attached to the body. Therefore, the exoskeleton device is designed for lifting heavy objects (15-90 kg), and the degree of freedom of body movement is limited by the external frame. When carrying a relatively heavy object weighing 10-30 kg, which is the intermediate range targeted by each type, the existing endoskeletal mechanism requires a stronger elastic material, but simply using the elastic one makes it difficult to move due to load on the body. Besides, using a high-powered exoskeleton mechanism would result in excessive support when considering the power-to-weight ratio. The structures considered in this study are intended to have the features that incorporate the positive aspects of both endoskeleton and exoskeleton types and to support carrying and walking with intermediate assisted force for existing assistance devices.

2 METHOD

2.1 Body structure and tensegrity

The human body is composed of a combination of elastic muscles and tendons, and discontinuous skeleton connected by elastic components. Furthermore, it has the characteristics of a structure composed of elastic and compressive components. This hybrid structure is called a "tensegrity"(tensional + integrity) structure. When the concept of tensegrity is applied to the structures of organisms, it is called biotensegrity accurately.

Originally, Buckminster Fuller proposed the concept of tensegrity and defined it as "a structural-relationship principle in which structural shape is guaranteed by the finitely closed, comprehensively continuous, tensional behaviours of the system and not by the discontinuous and exclusively local compressional member behaviours" (Fuller and Applewhite, 1975). Compared to existing structures consisting of stacked rigid bodies, the tensegrity structure can be lightweight by replacing some components of the rigid bodies with tensile materials such as wire while maintaining its stability. In addition, the entire structure can deform flexibly due to strain distribution when external forces are applied. Tensegrity structures have been studied and utilized especially in the field of architecture.

https://doi.org/10.1017/pds.2023.129 Published online by Cambridge University Press

Recently, the fields in which tensegrity is applied to have been expanding including robotics and space structures engineering, focusing on such properties as their light weight and deformation flexibility.
By focusing on the tensegrity structures that are inherently inside the body and extending the fundamental property of tension transmission, we devised that it could be utilized for new areas, especially assisting physical movement such as carrying heavy loads. Therefore, the authors construct a tension transmission function outside the body by utilizing wearing tensegrity structures.

2.2 Properties of tensegrity structure

The properties of tensegrity structures are analysed and categorized into seven characteristics (Ingber and Landau, 2012). With reference to these characteristics, we classify them into the following four items that are relevant to the design of wearable tensegrity structures for assisting physical movement.

1. Lightness

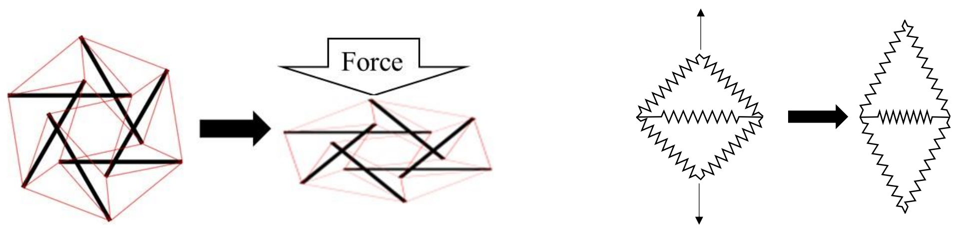
Tensegrity structures can be constructed by replacing certain components of structure consisting only of rigid materials with tensile materials such as wire. This replacement allows the same strength of the original structure while significantly reducing the amount of rigid material used. In comparison to structures of only rigid materials, a stable structure can be created using fewer rigid materials, resulting in lighter overall structure by using tensegrity structures. Recently, research have also been conducted in the field of robotics, taking advantage of their light weight and high flexibility. For example, a robot using tensegrity structure has an load capacity of 7.5 times its own weight, enabling a lighter structure than robots and vehicles based on existing structures (Wang et al., 2019).

2. Tension propagation

Tensegrity structures can be in a balanced state without providing external forces due to the initial tension in the tensile members. When an external force is applied and the tension in some of the tensile members increases, this change is distributed throughout the system, causing the entire tensile member to balance in a tauter state. In cases where tensile members are elastic, the structure can deform drastically without failure as shown in Figure 1(a). Even if one of the tensile members is detached or one of the compressive members breaks, the entire structure remains balanced in a slightly loose state without collapsing.

3. Deformation and increased stiffness

As deformation proceeds, more members are oriented in the direction of the external force, resulting in reduced deformability. Figure 1(b) shows an image of increased stiffness.



(a) Great flexibility of tensegrity structure, adapted from (Myers, 2014)

(b) Image of increased stiffness responding to stress non-linearly, adapted from (Chen and Ingber, 1999)

Figure 1. Properties of tensegrity structure

Pulling in the arrow direction compresses the central spring, and eventually the structure stiffens in the arrow direction. In other words, even if the relationship between strain and force at each tensile material is linear, the larger the load, the more nonlinearities emerge due to deformation of the structure. In a study focusing on the high flexibility, a multi-axis joint using a tensegrity structure was constructed (Lessard et al., 2016). By externally pulling a wire, or a tensile material, the length of some wires in the structure changes, allowing the joint to bend in multiple axes.

4. Hierarchy, extensibility, and modularity

Tensegrity structures can be connected to multiple structures and can even be nested hierarchically. When connected, multiple tensegrity structures share a tension network and are integrated. In other words, when an external force causes a change in tension in one structure, the change is transmitted as tension to other connected structures.

https://doi.org/10.1017/pds.2023.129 Published online by Cambridge University Press

2.3 Required functions of wearable tensegrity structures

In this study we design wearable tensegrity structures that are intended to assist body movements. Therefore, this study focuses on at least two functions: the structure must be able to deform in accordance with body movements, or flexibility, while it must be able to sustain itself independently, or rigidity. The more specific functions required for this structure are considered in the following four categories.

1. Degree of freedom

While carrying a heavy load, the whole body moves, including rotation, flexion, and extension of the trunk. When the body wears the tensegrity structures, it is necessary to provide sufficient flexibility, or degree of freedom, enabling these movements. Specifically, the structure should allow flexible deformation such as tension, compression, bending, and torsion. In addition, the left and right lower limbs should be able to move independently while responding to the extension and flexion of each joint. The structure must be constructed so that it can follow body movements without disintegrating, while maintaining a certain degree of freedom.

2. Rigidity

When the structure is worn by the user the structure must have sufficient rigidity to support a heavy load. The future goal is to support a physical load equivalent to the body weight of user. In order to support heavy objects in place of the body while minimizing the physical load on the body due to the self-weight, the structure must be lightweight while having sufficient rigidity, i.e., it must have high specific strength. Furthermore, since the structure may collapse if the load is concentrated on a particular area, the structure that can distribute the load over the entire structure is suitable for use.

3. Connection to the body

The structure attached to the user must be able to follow the body movements as described in 1 while reducing the load on the body in carrying heavy objects. Fundamentally, the structure is positioned on the ground to support the weight, with its lower end fixed at the foot. In addition, structure-body connection is provided at joints such as knee and hip to correspond to the movement of the lower limbs and torsion of the trunk during walking. To propagate tension throughout the structure while following the movement of the joints, connections must be made at the joints so that the tension network is not fragmented.

4. Scalability

The structure must be scalable so that it can be worn by variety of users, as each individual has different body size, height, and flexibility. To fit the best structure for each user, it is necessary for the structure to be easily adjustable in size and length. The combined unit of compressive and tensile materials is required.

3 DESIGN AND IMPLEMENTATION

3.1 Shape of the structure

For the functions shown in 1 and 2 in 2.3, we considered the basic shape of the tensegrity structure in exploratory manner, building a model of the structure.

First, we target at supporting to carry heavy loads on the back. Full-body movements include rotation, flexion, and extension of the trunk and swinging of the lower limbs during walking. The structure should follow these movements and maintain rigidity even under heavy loads. Therefore, we focused on the function of the spine, which maintains the body itself and serves as the basis for movement throughout the body. Furthermore, regarding function 4 in 2.3, the structure must also be able to adjust its total length, as it must be able to expand and contract to fit the physical size of the users. A pure tensegrity structure consisting only of tensile and bar compression materials has high flexibility and provide excessive freedom of body motion to be stable. Thus, the structure must be more suitable for rotation, flexion, and extension of the trunk. Therefore, a hybrid structure is used for the purpose.

A hybrid structure is one in which the compression member takes on some of the functions of the tensile member, in contrast to a full tensegrity structure in which the compression member is a bar-shaped member. As a result, the shape of the rigid material is more complex and has a relatively low degree of freedom. In this study, we focused on the hybrid structure devised by Tom Flemons based on the vertebrae (Flemons, 2007), and constructed a prototype model as shown in Figure 2(a). Our

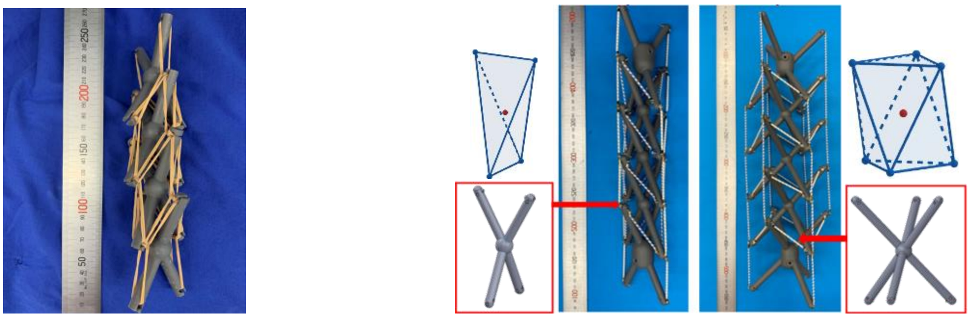
https://doi.org/10.1017/pds.2023.129 Published online by Cambridge University Press

prototyped unit consists of a sphere at the centre of the tetrahedron with four triangular faces and four struts extending to four vertices of a tetrahedron from the centre. This is called as tetrahedral unit (Flemons, 2007). The tensegrity structure is constructed by connecting the tips of the struts with tensile material. It is capable of bending, tensile, compressive, and torsional deformation, while maintaining rigidity under tensile and compressive loads, allowing it to follow the body movements.

When a compressive load was applied to the prototype structure, assuming it was to support a heavy load, we found the following issues. First, the combined unit structure exhibited high deformability and excessive degrees of freedom. In response, we decided to reduce the number of units to limit the degrees of freedom. Specifically, the units with double and triple in length were designed by lengthening the longitudinal compression material, and a reduction in flexibility was confirmed by building the mock-up model.

Second, when the structure is compressed, a sudden decrease in stiffness, such as buckling, occurs. Therefore, the first step was to change the tensile material. In our prototype, we used rubber bands but switched to elastic shock cords for greater exerting tension. In this study, we assumed that a 20 kg weight will be supported by four structures, front and rear of the body, as described in 3.3. Therefore, each structure must have sufficient stiffness against 5 kgf load. The prototype structure was not rigid enough to withstand the load, and buckling-like phenomena occurred. Therefore, the number of pillars in the unit was increased from four (tetrahedral) to six (octahedral).

Using shock cord as a tensile material and 3D printed parts (Grey resin V4, Formlabs) as a compressive material, two structures were constructed respectively by connecting five tetrahedral units with four struts and by connecting five octahedral units with six struts. The latter hybrid structure on the right in Figure 2(b) consists of a sphere at the centre of the octahedron with eight triangular faces and six struts extending to six vertices of an octahedron. This is called as octahedral unit (Flemons, 2007). Performance tests were conducted to investigate the degree of shrinkage of each structure under load in the compressive direction, and the results are shown in Figure 3. The tetrahedral unit buckled at 13.2 N, resulting in a loss of stiffness, and therefore no higher load was applied. On the other hand, the octahedral unit did not buckle at 54.4 N, demonstrating a proportional relationship between deformation and load. The new unit increases its stiffness against compression force from 0.28 N/mm to 0.43 N/mm (when 5 units are connected). Therefore, the problem of reduced stiffness in compression was improved. Finally, the basic structure was determined, and columnar tensegrity structures were constructed as shown in Figure 2(b).



(a) Prototyped hybrid structure *(b) Tetrahedral unit (left) and octahedral unit (right)*

Figure 2. Hybrid tensegrity structures

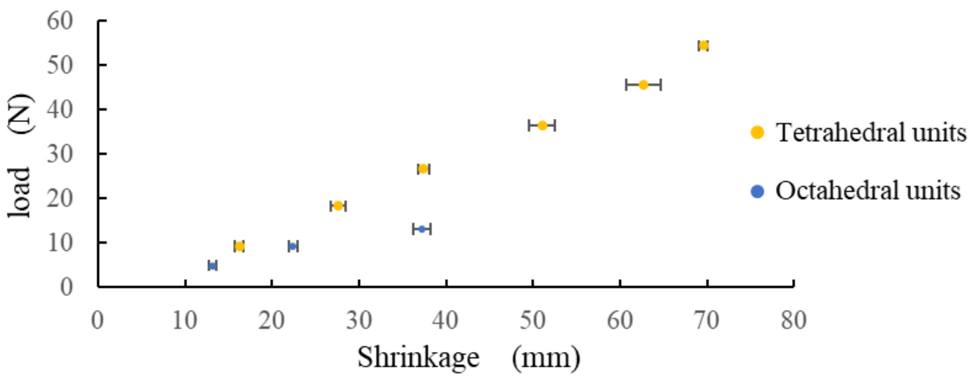


Figure 3. Relation between shrinkage and compressive load

https://doi.org/10.1017/pds.2023.129 Published online by Cambridge University Press

3.2 Placement of the structure on the body

The placement of the columnar tensegrity structures on the body is considered. The placement must allow sufficient degrees of freedom for full-body movements such as trunk rotation, flexion, and extension, and must be capable of assisting in carrying heavy objects. The spine is located at the centre line of the back, while in this study, we decided to use two spinal columns on the coronal plane of body, one on the left and one on the right, separated from the centre line of the body. Furthermore, we have decided to connect the upper body to the sole of each foot using a tensegrity structure. This placement enables independent movements of the left and right lower limbs. During walking, the left and right structures are expected to deform separately and perform different functions, such as supporting stability during the stance phase and flexibility during the swing phase. Furthermore, by placing these structures on the front and back sides, we consider that they will provide more assistance in carrying heavy objects. Figure 4 shows the placement of these structures.

3.3 Wearing method

Only the upper and lower ends of the structure are connected to the body from the viewpoint of connection to the body as described in the function 3 in Chapter 2.3. This is because the tension propagation function, which is one of the characteristics of tensegrity structures, cannot be fully utilized if the structure is divided at any part other than the upper and lower ends. The upper end is fixed at upper chest and at scapula back. The 3D printed hybrid structure at the upper end, shown in Figure 4(a), was connected to a protector jacket for motorcycles. The lower end of the structure is connected to a snowshoe-type equipment. By integrating the structure with the foot of user, the load applied to the structure and the structure self-weight are supported on the ground. In addition, linear guides were attached vertically at the waist and lower knee joints to connect the structure to the body. The linear guides allow tension propagation because the structure is not completely fixed. As a result, the entire structure can deform in accordance with the body movements of user while maintaining a constant distance from the body.

Based on the above, the devised wearable tensegrity structures are shown in Figure 4(a). The total length of the structure is approximately 1250 mm, and the total weight is 7.2 kg.

Authors confirmed that various body movements are possible while wearing the structures, such as flexion, extension, and rotation of the trunk as well as flexion and extension movements of the lower limb. Figure 4(b) shows some of movements.

(a) Wearing the tensegrity structures and connections between user and the structures

(b) Trunk flexion and rotation movements with structures

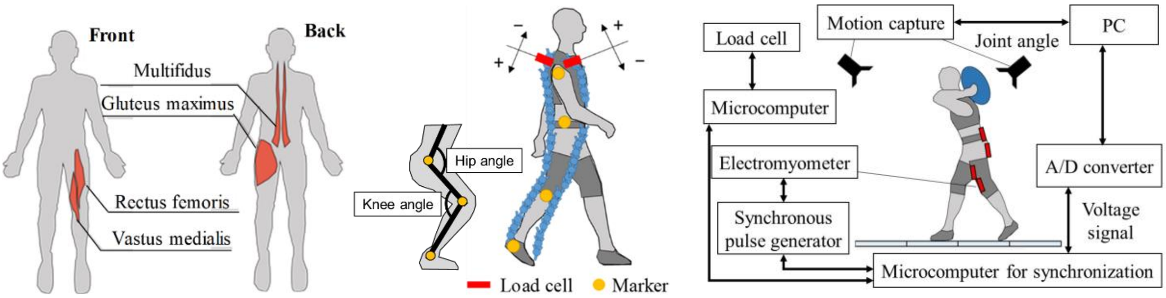
Figure 4. Wearable tensegrity structures

3.4 Measurement method

To investigate the effects of the structures on body movements when wearing the structures and carrying heavy objects, the authors constructed a system for experiment. In the system, joint angles, floor reaction force, electromyograms, and tension of the structure can be measured. Joint angles were measured by motion capture (Raptor-E, Motion Analysis). Floor reaction force was measured by force plates. The structure tension was measured with a load cell. EMGs were measured (LP-WS1224, Logical Product Co.) for the four muscle activities shown in Figure 5(a). The multifidus muscles involved in upper body raising and spinal balance, the gluteus maximus and vastus medialis muscles

https://doi.org/10.1017/pds.2023.129 Published online by Cambridge University Press

involved in hip and knee joint extension during walking, and the rectus femoris muscle involved in lower limb swing and knee joint coordination during walking are measured. Figure 5 shows the muscles to be measured, the measurement position of the structure tension, position of markers for motion capture and the system configuration.



(a) Target muscles *(b) Measurement position and position of markers* *(c) Experimental system configuration*

Figure 5. Experimentation environment

4 EXPERIMENT

4.1 Procedure

The authors investigated how wearing tensegrity structures work in carrying heavy load. The experiment described below was conducted under the conditions of maintaining standing posture and walking with/without structure and weight. In this study, the protector jacket and attachments that are worn on the body were specifically sized for two persons, who designed and constructed this structure, with approximately the same body size (males, 22 years old, height 168 cm/165 cm, weight 50 kg/55 kg). Although the tensegrity structures are scalable and can accommodate a range of body sizes, only one size is available, and it was tested with two developers who could fit it. The position of motion capture markers are shown in Figure 5(a)(b) and the sampling rate of motion capture camera, floor reaction force meter, and electromyograph were 200 Hz. Strain gauges were attached to the connection between the structure and the body to measure the tension in the tensegrity structures. A sandbag as weight was placed on the back near the shoulders and held in place by hands to prevent it from sliding. As described in Chapter 3, a 20 kg weight was assumed, but for safety reasons, a 16.4 kg sandbag was used.

In the posture maintenance experiment, the subjects maintained a standing posture for 10 seconds under four different conditions: with and without the structures, and with and without the weight. Three trials were performed in each condition.

Next, in the walking experiment, the subjects moved a distance of 4 m at a pace of 80 bpm with a stride length of 500 mm. The subjects performed both sliding-step walking and normal walking. During sliding-step walking, subjects slid their feet without lifting their soles off the ground. Four conditions were performed: with and without the structures, and with and without the weight. In the normal walking, subjects were not given any instructions on how to walk, and they moved in their own matter. Two conditions were tested with structures: with and without the weight. Three trials were performed for each six conditions.

The results of the experiments were statistically analysed using Bonferroni multiple comparison test.

4.2 Results

4.2.1 Posture maintenance experiment

The EMG signals were integrated over a 10-second period during postural maintenance. The average of three trials was calculated to compare the muscle activity under each condition. The integrated EMG signals of each muscle of the two subjects are shown in Figure 6.

In subject A under the condition of shouldering a weight on the back, wearing the structures decreased the muscle activities of the multifidus, vastus medialis, and rectus femoris muscles, and increased only the activity of the gluteus maximus muscle. In contrast, in subject B under the condition of shouldering a weight, wearing the structures increased the muscle activity of the multifidus, gluteus

https://doi.org/10.1017/pds.2023.129 Published online by Cambridge University Press

maximus, and vastus medialis, and slightly increased that of the rectus femoris muscle. As shown in Figure 6, there were significant differences in the gluteus maximus muscle of subject A and the three muscles of subject B between conditions with and without the structures (a and b, c and d).

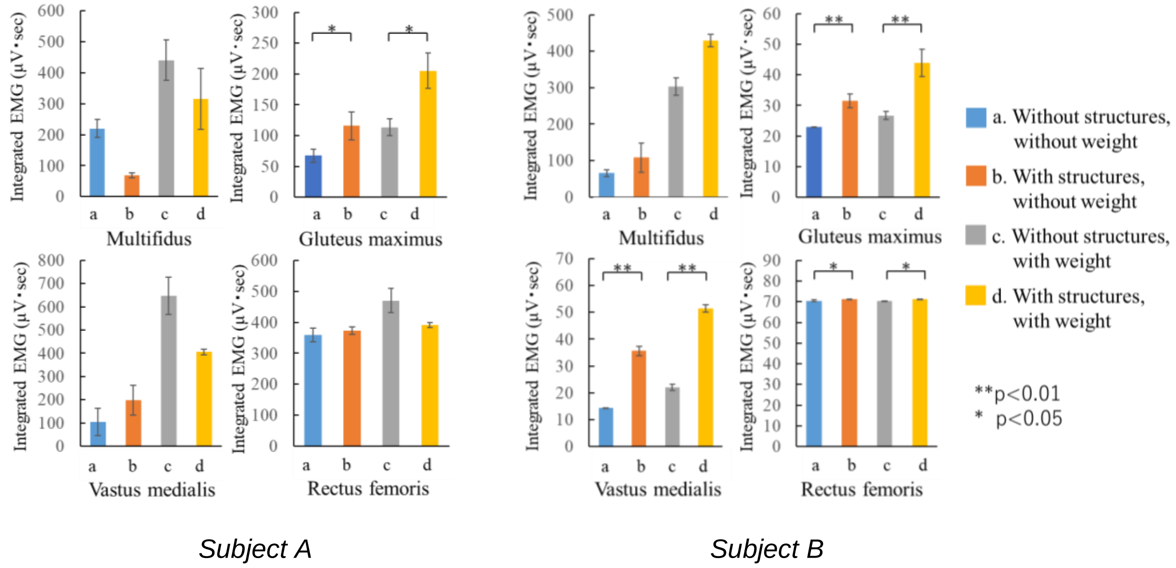


Figure 6. Muscle activities in each condition of the posture maintenance experiment

4.2.2 Walking experiment

The gait cycle was measured based on the joint angles from the motion capture data, and the EMG signals were integrated over two gait cycles, starting at the initial swing of the left foot. To compare the muscle activities, the timescale was normalized by dividing it by the duration of the two gait cycles. Muscle activities of each muscle of the two subjects are shown in Figure 7.

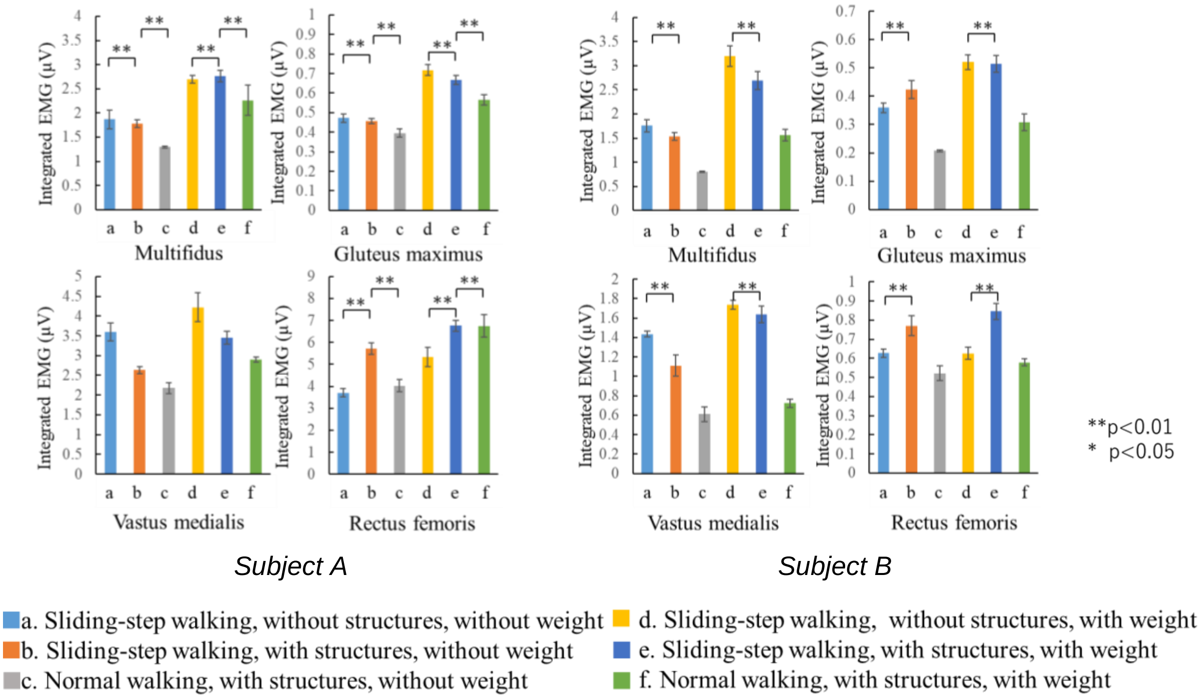


Figure 7. Muscle activities in each condition of the walking experiment

In both subjects, with wearing the structures, muscle activities tended to be lower during normal walking (c, f) than during sliding-step walking (b, e), regardless of with or without weight. This was especially observed in subject B. As shown in Figure 7, there were significant differences in the three muscles of subject A and the all four muscles of subject B between conditions with and without the structures (a and b, d and e). Furthermore, there were significant differences in the three muscles of subject A between conditions sliding-step and normal walking (b and c, e and f).

https://doi.org/10.1017/pds.2023.129 Published online by Cambridge University Press

5 DISCUSSION

We consider how wearing tensegrity structures work on body action in carrying load. The results of the postural experiment showed that in subject A, wearing the structures decreased the activities of the multifidus, vastus medialis, and rectus femoris muscles in the condition of shouldering weight. In contrast, in subject B, wearing the structures increased the activities of the multifidus, gluteus maximus, and vastus medialis muscles under the same conditions. To understand the differences in results between the two subjects, we focused on the joint angles. Generally, in the knee and hip joints in a standing position, the moment arms around the joints become longer by bending the joints, resulting in an increase in load torque compared to the state in extending joints. The average angles of the hip and knee joints of the subjects are shown in TABLE 1.

TABLE 1. Hip and knee joint angles in each condition of the posture maintenance experiment

Subject A (Mean ± SD)

Condition	a	b	c	d
Hip (°)	177.6±0.82	153.6±2.36	157.3±2.39	150.5±3.96
Knee (°)	167.4±2.36	157.7±8.04	142.6±4.75	149.7±2.44

Subject B (Mean ± SD)

Condition	a	b	c	d
Hip(°)	177.5±2.39	131.8±0.17	163.7±1.87	139.4±4.33
Knee(°)	168.4±0.17	155.5±1.22	171.5±1.20	155.6±3.67

a. Without structures, without weight, b. With structures, without weight, c. Without structures, with weight, d. With structures, with weight

Under the condition of shouldering weight, subject A showed a little change in the knee and hip joint angles between wearing the structures and not wearing the structures (a and b, c and d), while joints of subject B bent more in the condition of wearing the structures than in the condition of not wearing the structures. This increased the activity of the gluteus maximus muscle, which extends the hip joint and that of the medial vastus medialis muscle, which extends the knee joint.

Next, the results of the walking experiment showed that when subjects were wearing the structures, there was a tendency for muscle activity to decrease during normal walking compared with sliding-step walking, regardless of weight added. To understand the factor, we focused on the angular range of the hip and knee joints during walking. The angular ranges of the hip and knee joints of subjects obtained from the motion capture results are shown in Figure 8.

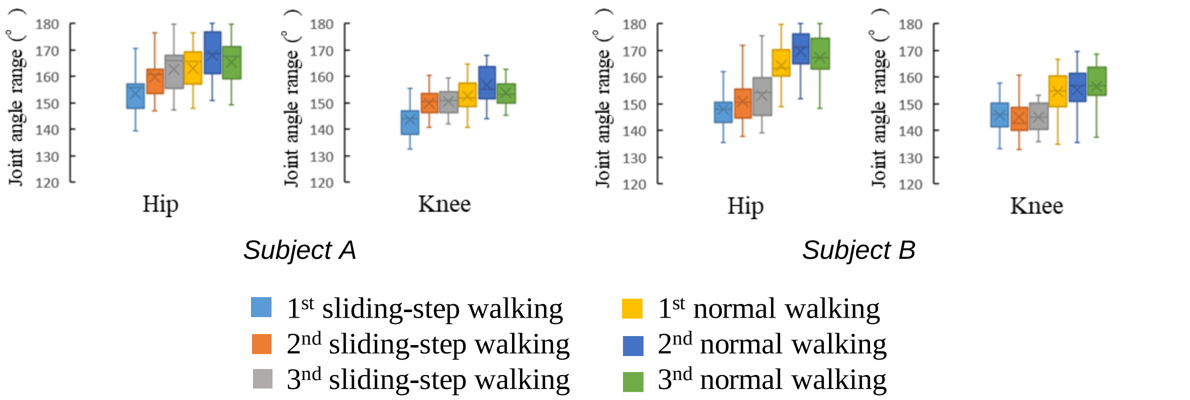


Figure 8. Joint angle ranges of the walking experiments with the structures and the weight

The hip and knee joints tended to be more extended during normal walking compared to the sliding-step walking. This extension of each joint during walking resulted in decreased muscular activity of the multifidus muscle for spinal erection, the gluteus maximus muscle for hip extension, and the vastus medialis and rectus femoris muscles for knee extension.

After considering the results of both experiments, it was found that using structures with extended knee and hip joints had the effect of reducing the muscle activity during walking.

Additionally, the subjects reported that they had a sensation that their body is being pushed up by the structures connected to the front of the body. They also reported an increase sense of stability in walking while supporting a weight. These findings suggest that the body can be assisted in walking and carrying a weight by wearing the structures.

In order to efficiently use the tensegrity structures for supporting body action, it is necessary to further investigate ways to resolve the trade-off between stiffness for reduced muscle activity and flexibility for

https://doi.org/10.1017/pds.2023.129 Published online by Cambridge University Press

ease of movement. Therefore, combining pure tensegrity structures with higher flexibility around joints and the hybrid structures in this study can be considered. In particular, it would be possible to satisfy the stiffness and flexibility around the joints by using the property of non-linearly increasing stiffness with deformation, as shown in 2.2-3, so that as the joint flexes, it becomes more difficult to bend.

6 CONCLUSION

Our research focused on the tension propagation function throughout the body in consideration of a new method of supporting body action. For this purpose, we designed experimental wearable tensegrity structures.

General tensegrity structures have unique characteristics in lightness, tension propagation, deformation, increased stiffness, hierarchy, extensibility, and modularity. Taking into account the advantages, we devised a columnar-shaped tensegrity structure, with a focus on the spine, which is involved in the whole-body movements. Since the pure tensegrity structure has a high flexibility in following the body movements, a hybrid structure was considered with reference to spine model proposed by Flemons. In order to achieve the desired level of flexibility to follow the body movements, we constructed the tensegrity structures by integrating multiple octahedral units, and confirmed that the structures satisfied the rigidity under compression.

We also confirmed that the structures worn on the body had sufficient degrees of freedom to follow the rotation, bending of the trunk, and walking movements.

Subsequently, an experimental system capable of measuring electromyograms, joint angles, and structure tension was constructed. We investigated the effects of wearing the structures while carrying heavy load. The results indicated that muscle activity tended to decrease when the structures were used under conditions of joint extension. These suggest that the tensegrity structures possess the potential to support body action in various postures and to reduce muscle activity during weight carrying. In the future, we aim to solve the trade-off between stiffness and flexibility around the joints for effective support by integrating hybrid structures and pure tensegrity structures.

The new wearable tensegrity structures on the body demonstrates the further potential of tensegrity, and this study will contribute to the field of structure design applying the tensegrity to.

ACKNOWLEDGMENTS

This work was supported in part by JSPS KAKENHI JP20K11923 and by the project “Study on Human Dynamics Measurement” of the Research Institute for Science and Engineering, Waseda University. The authors would like to thank Gaku Tamaki, Yoshiki Aoki, and Takato Wakuda for their help.

REFERENCES

Chen, C.S. and Ingber, D. E. (1999), “Tensegrity and mechanoregulation: From skeleton to cytoskeleton,” *Osteoarthritis and cartilage*, vol. 7, no. 1, pp. 81–94. https://doi.org/10.1053/joca.1998.0164.

Flemons, T. (2007), “Geometry of Anatomy.”, *Intension Design*, Available at: http://intensiondesigns.ca/geometry-of-anatomy (accessed Apr. 2, 2023)

Fuller, R. B. and Applewhite, E. J. (1975),"Tensegrity", In: Fuller, R. B. and Applewhite, E. J. *Synergetics: explorations in the geometry of t*hinking, Macmillan, New York, p.372.

Ingber, D. E. and Landau, M. (2012), “Tensegrity”, *Scholarpedia*, Available at: http://www.scholarpedia.org/article/Tensegrity (accessed Apr. 2, 2023). https://doi.org/10.4249/scholarpedia.8344

Inose, H., Mohri, S., Yamada, Y., Yokoyama, K., Kikutani, I. and Nakamura, T. (2017), “Verification of Effective Assistance by Endoskeleton-type Power Assist Suit based on Musculoskeletal Simulation.” *Journal of the Robotics Society of Japan*, Vol. 35, No. 7, pp. 557–565, https://doi.org/10.7210/jrsj.35.557

Kumamoto, M., Oshima, T. and Yamamoto, T. (1994), “Control properties induced by the existence of antagonistic pairs of bi-articular muscles- Mechanical engineering model analyses.” *Human Movement Science*, Vol.13, pp.611-634. https://doi.org/10.1016/0167-9457(94)90009-4

Lessard, S., Bruce, J., Jung, E., Teodorescu, M., SunSpiral, V. and Agogino, A. (2016), "A lightweight, multi-axis compliant tensegrity joint", 2016 IEEE International Conference on Robotics and Automation (ICRA), pp. 630-635. https://doi.org/10.1109/ICRA.2016.7487187.

Myers, T. W. (2014), “Anatomy Trains: Myofascial Meridians for Manual and Movement Therapists,” Elsevier Health Sciences, London.

Wang, Z., Li, K., He, Q. and Cai, S. (2019), “A Light-Powered Ultralight Tensegrity Robot with High Deformability and Load Capacity”. *Advanced Materials (Weinheim)*, Vol. 31, No. 7, whttps://doi.org/10.1002/adma.201806849.